ESTF2021 Virtual Series

June 3, 2021 | 1:00 ET

CloudCube: a compact, multi-frequency mm-wave radar

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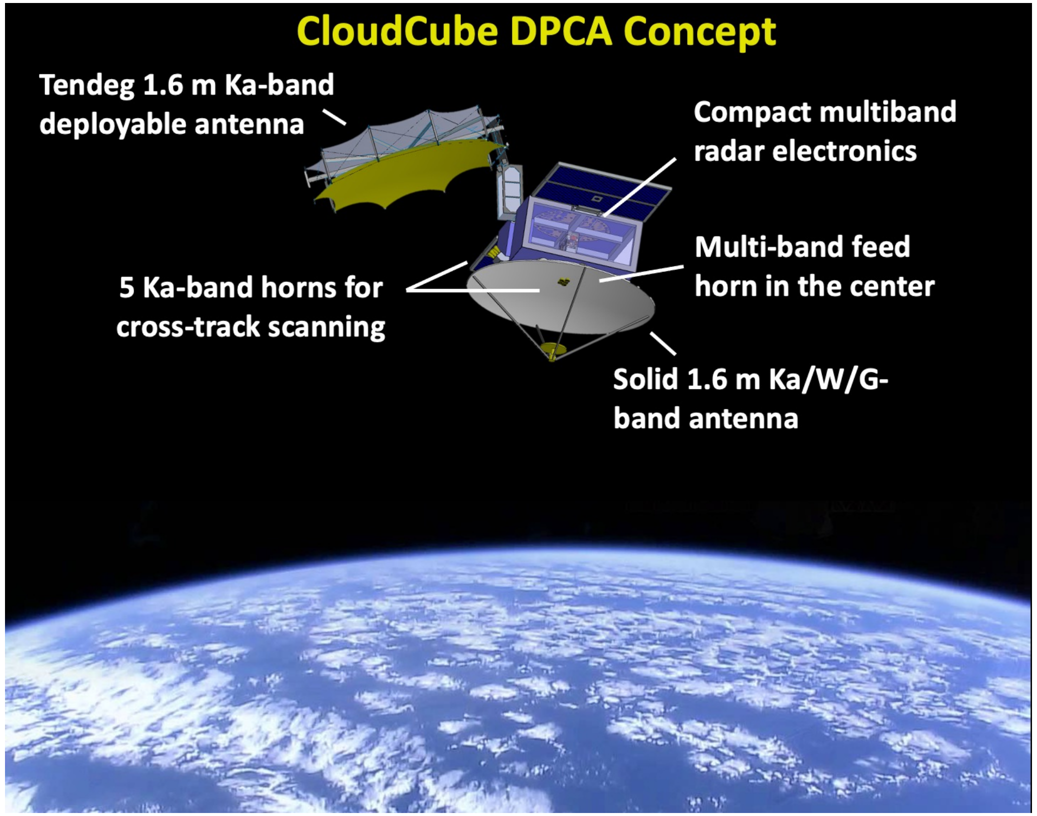
Jet Propulsion Laboratory
California Institute of Technology

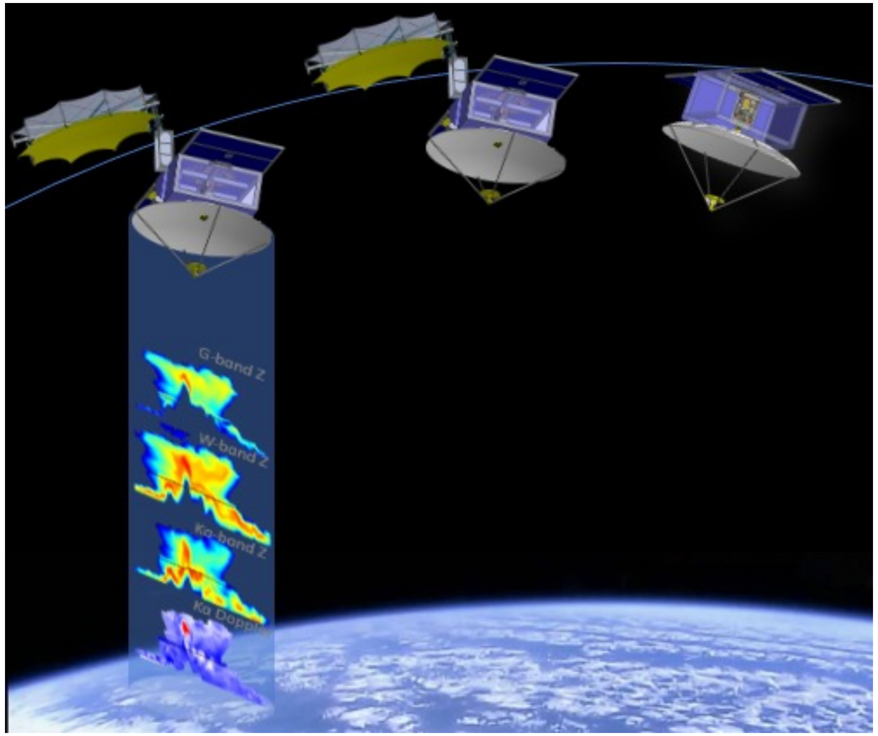
CloudCube: Introduction



- CloudCube is been developed under the NASA ESTO Instrument Incubator Program (IIP) 2019.
- CloudCube combines 3-band radar electronics, using a minimalistic architecture that vastly reduces mass, power and size, development time and recurring cost.
- For the first time, CloudCube combines Ka-, W- and G-band (35/94/239 GHz, respectively) radar backscatter with Doppler velocity measurement capability at Ka-band.
- CloudCube instrument design is modular allowing for selection of different subsets of the radar frequencies to meet targeted mission observables from a resource-limited platform.

CloudCube: Science Objectives

- Obtain simultaneous cloud and precipitation vertical profiles at global-scale.
- Observe internal storm processes and dynamics from space for the first time.
- Improve understanding on cloud dynamical and microphysical processes and their roles in cloud-climate feedback and severe weather.



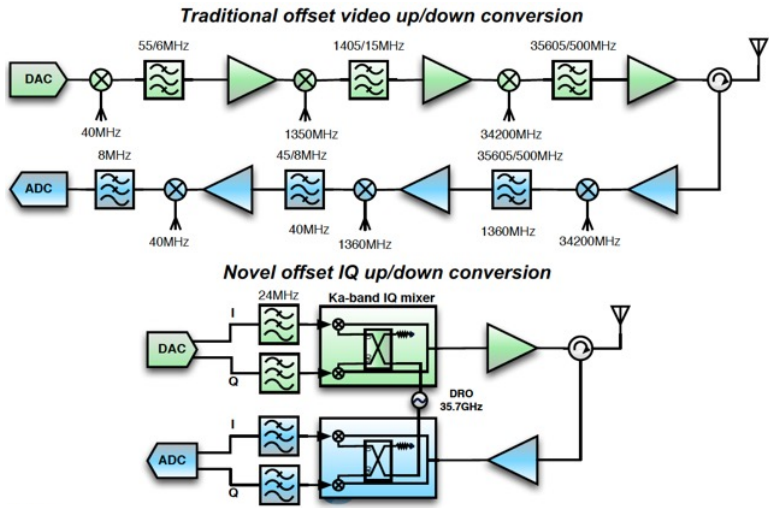
- Compact, affordable radar instruments facilitate the use of constellations of identical instrument flying in the same orbit to observe the evolution of weather processes with high-vertical profiling capabilities or in diverse orbits to increase sampling across the diurnal cycle.

Example of low-cost future constellation mission concept enabled by CloudCube development

Simulation of CloudCube's Ka/W/G-band radar reflectivities using RAMS model

How do we achieve small size/low power?

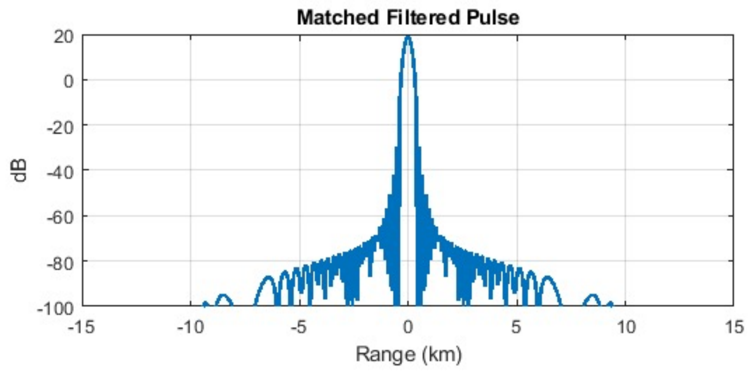
1.- New radar architecture offset IQ up/down conversion



- *Reduce the number of discrete RF components -> decreasing the mass and power*

Eval Peral et al. JPL NTR # 49760, "Offset IQ modulation technique for miniaturized radar electronics".

2.- Pulse compression techniques



- *Pulse compression enables low-power, high duty cycle transmitters to achieve the same sensitivity as their high-power, low duty cycle counterparts*

R. M. Beauchamp, S. Tanelli, E. Peral and V. Chandrasekar, "Pulse Compression Waveform and Filter Optimization for Spaceborne Cloud and Precipitation Radar," in IEEE Transactions on Geoscience and Remote Sensing, vol. 55, no. 2, pp. 915-931, Feb. 2017, doi: 10.1109/TGRS.2016.2616898.

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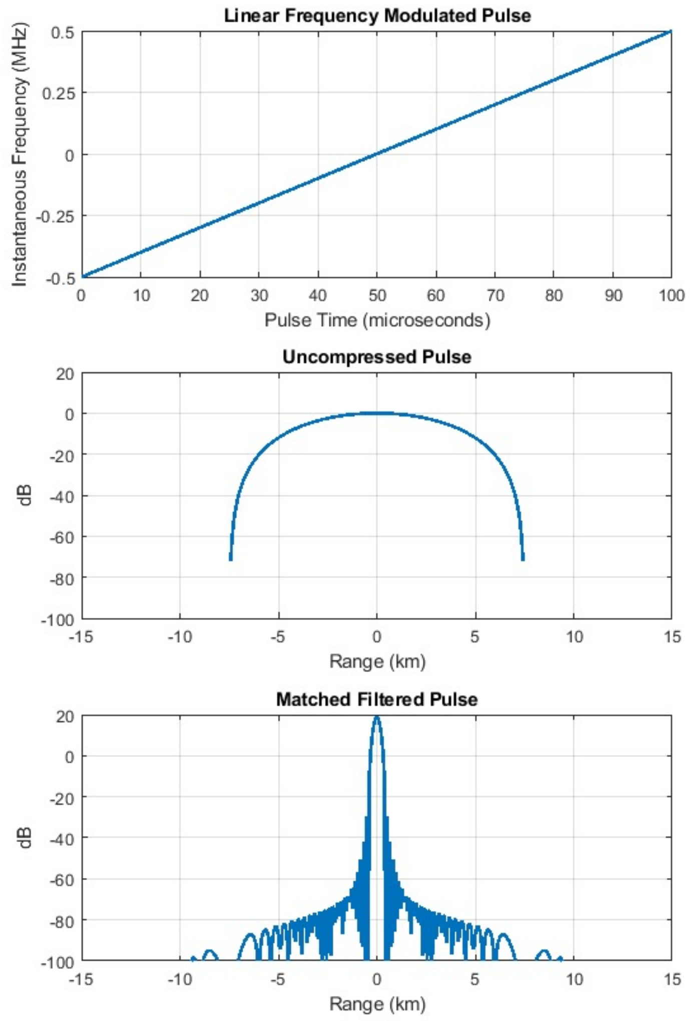
Pulse Compression

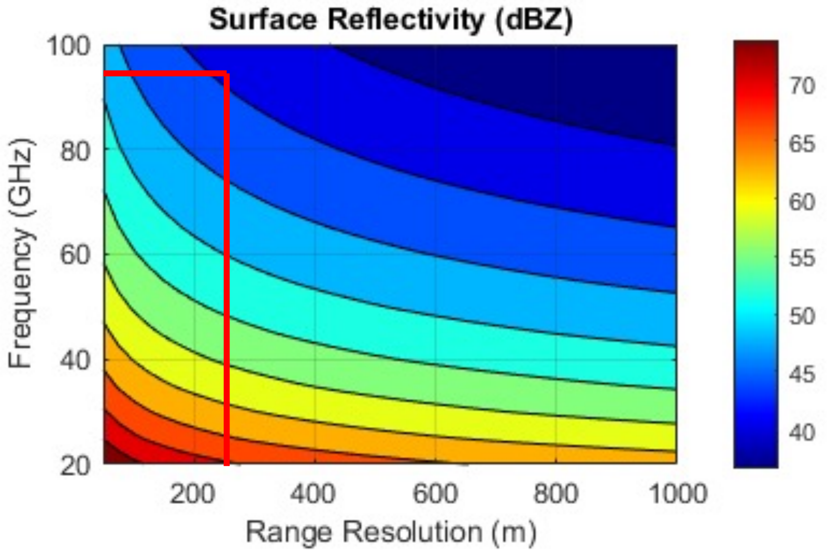
- Pulse compression is used to focus the long duration pulse to increase the SNR while achieving the desired range resolution.
  - The pulse compression gain is determined by the time-bandwidth product.
  - With a 20 dB pulse compression gain, a 10 Watt solid state transmitter can achieve the same sensitivity as a 1000 W short-pulse radar.
- Effective pulse compression must manage the range sidelobes. The range sidelobes from strong echoes (the ground) can mask weak echoes (clouds).

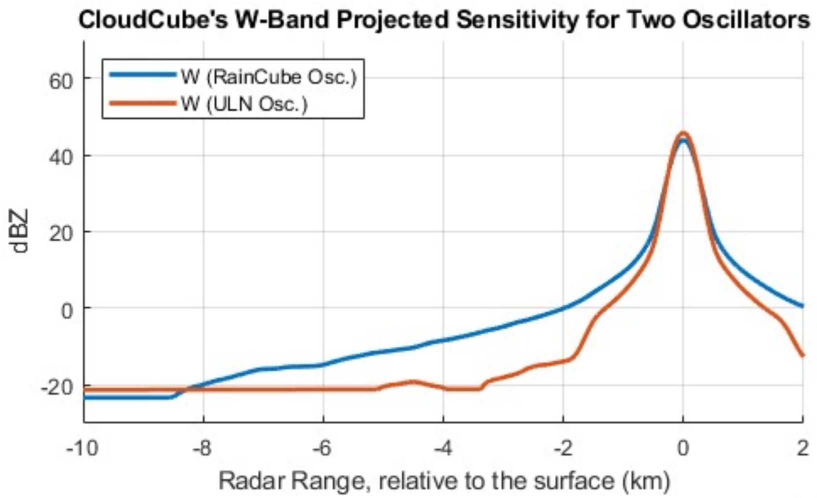


Pulse Compression

- Range Sidelobes-

- What pulse compression sidelobe level do we need?
  - This is determined by the ratio of the peak ground echo power to the minimum sensitivity.
  - The surface is the brightest target the radar will typically observe.
- Using the CloudCube W-band as an <u>example</u>:
  - Target minimum sensitivity is -20 dBZ @ ~250 m range resolution.
  - Surface reflectivity peak at W-band for a 10 dB NRCS with 250 m resolution is ~45 dBZ.
  - **Pulse compression range sidelobe level target is**
    - **45 dBZ - -20 dBZ = 65 dB.**
- Sources of range sidelobes performance degradation
  - Oscillator phase noise
  - Mixer Images
  - Amplifier nonlinearity

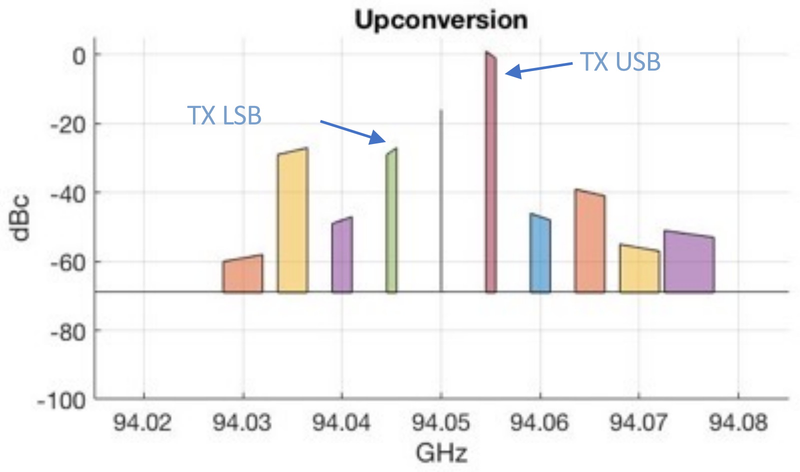


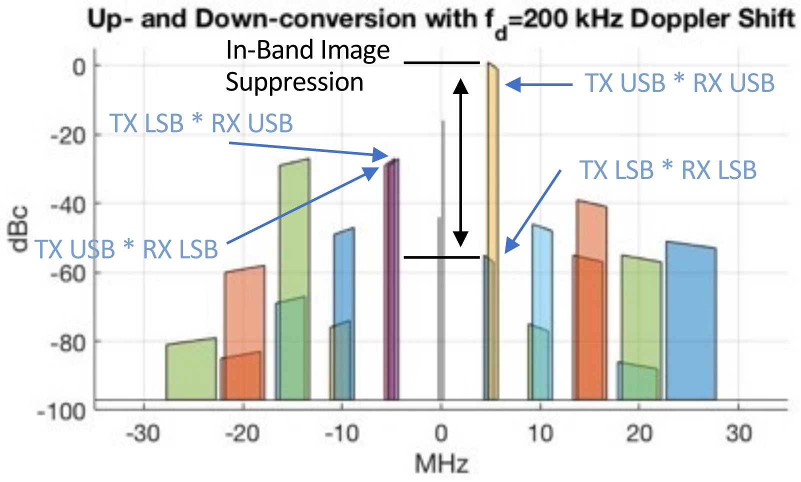


Pulse Compression

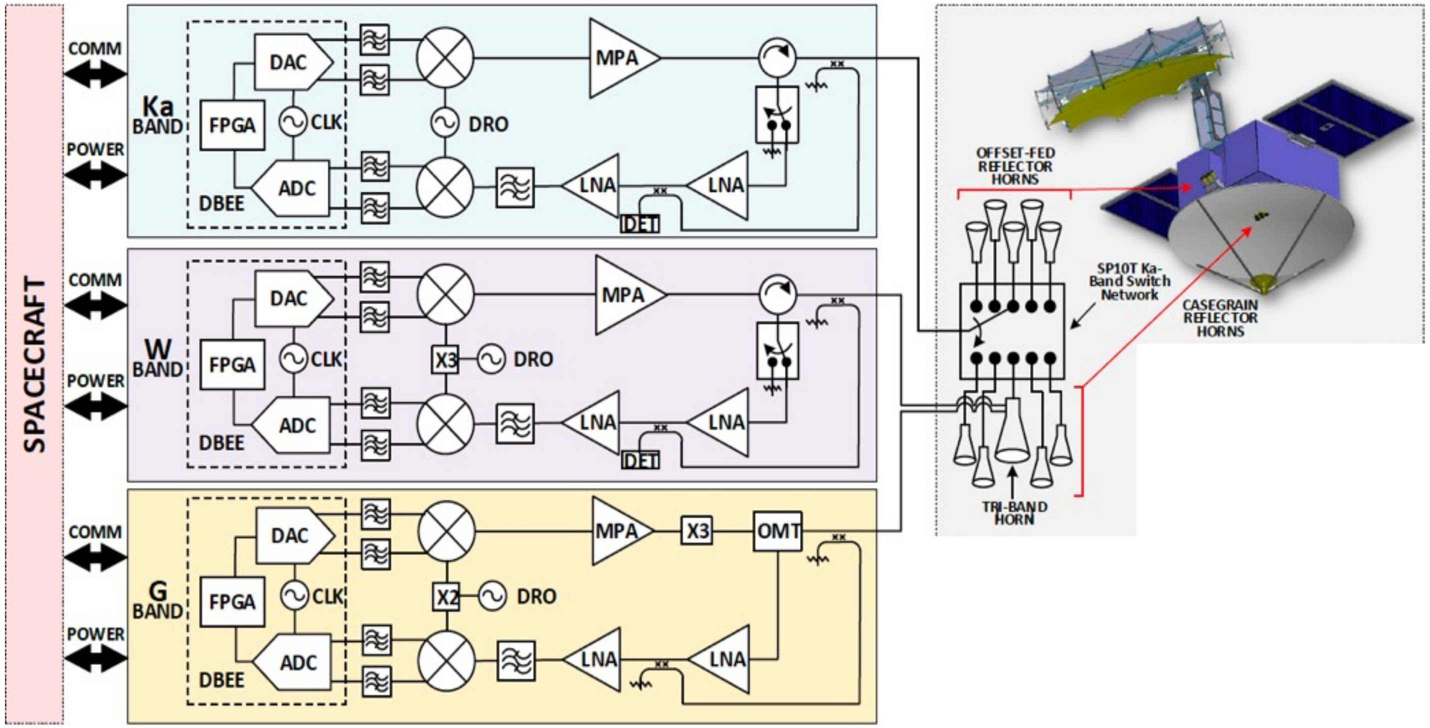
- Mixer Image Range Sidelobes-

- The IQ offset video technique uses the mixer to suppress the unwanted image sideband. If not suppressed, the image can overlay the signal of interest and act as a phantom target and a offset range (due to the Doppler range migration).
- The image, after up- and down-conversion, must be suppressed by more than the peak surface to minimum detectable signal.
- The IQ mixer's image suppression is sensitive to I/Q amplitude and phase imbalances.
  - Figure shows the intermodulation power measurements from a W-band IQ mixer.
  - A Doppler shift of 200 kHz illustrates the different intermodulation products.



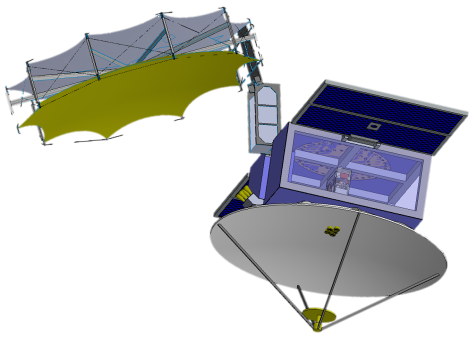


CloudCube Instrument Architecture

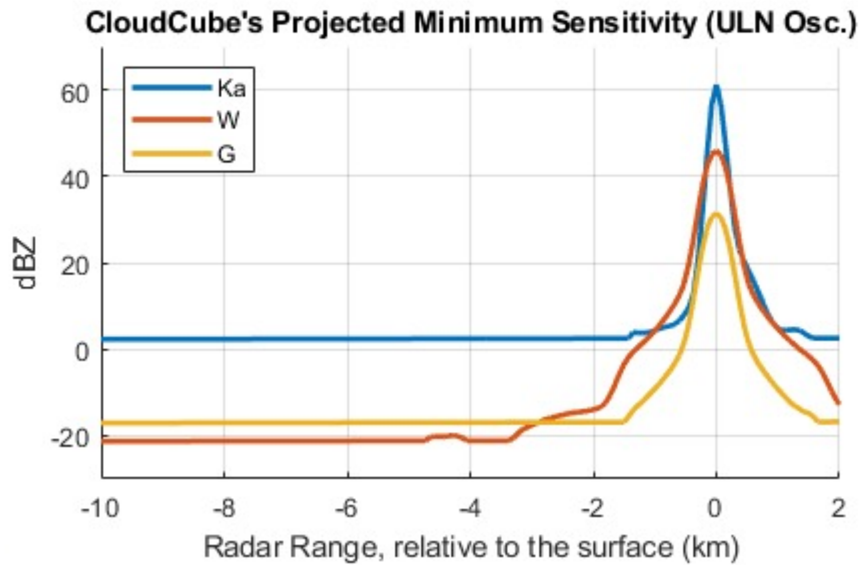


The architecture is composed of three modules (Ka-, W- and G- band), each of which has two main subsystems: a Radar Transceiver (RT) to generate the millimeter-wave power and detect the cloud/rain echoes with high accuracy, and a Digital processor and Back-End Electronics (DBEE) for the chirp pulsed waveform generation, timing and control of the radar to acquire and process the received echoes and estimate reflectivity and for Ka-band, Doppler velocity.

System Performance



The design of the electronics is constrained to mature solid-state components integrated in a compact architecture compatible with SmallSat accommodations. Such demanding power consumption and mass requirements set tight constrains on the radar design to meet the science requirements.



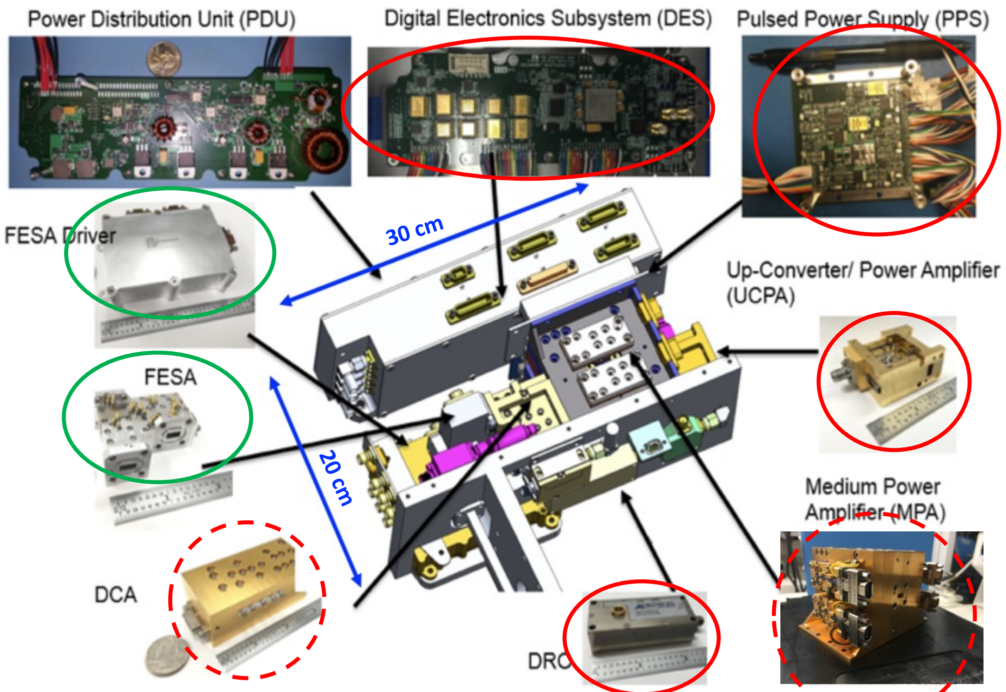
Simulated CloudCube minimum sensitivity, as a function of range, over an ocean surface. The simulation included thermal and phase noise.

Radar Parameters

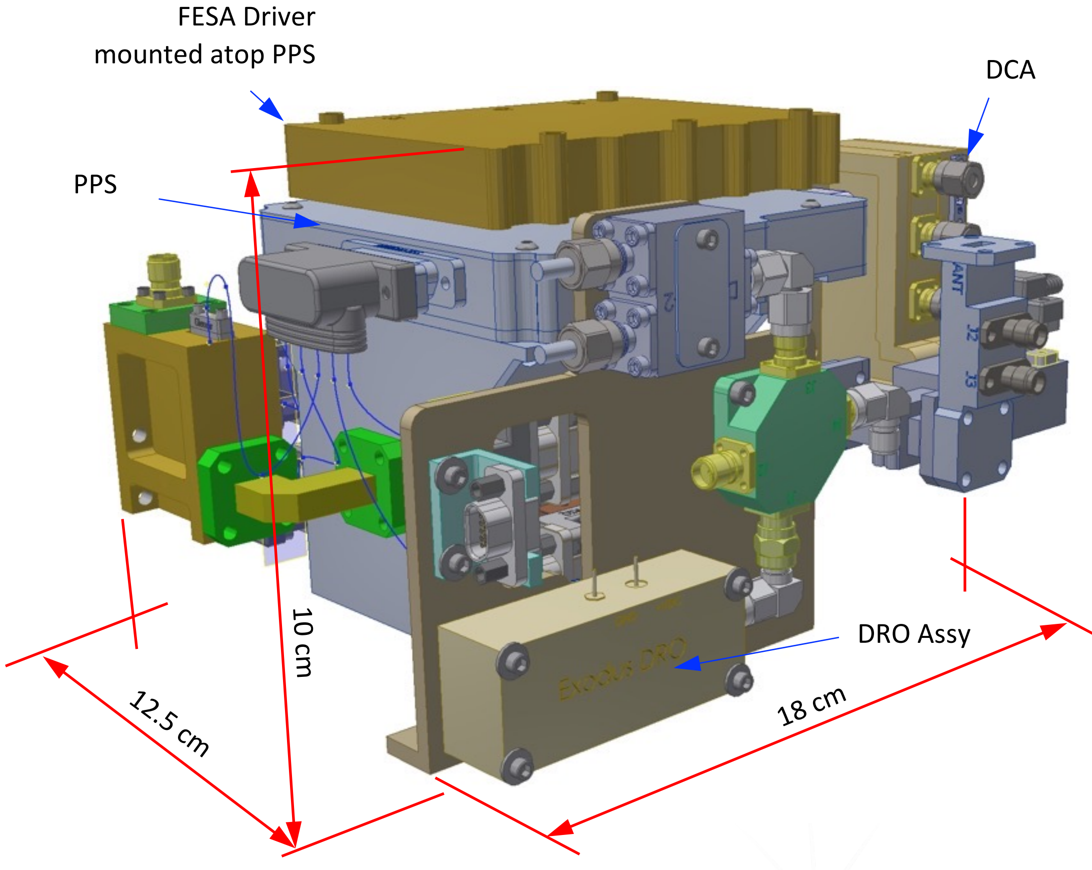
	Ka-Band	W-Band	G-Band
Fc (GHz)	35.75	94.05	239
TX Power (W)	10	40	1
NF (dB)	3	4	7
PRT (us)	250	1600	1600
Int Time (ms)	67	200	200
Altitude (km)	400		
Velocity (m/s)	7600		
Ant Diameter (m)	1.6		
Ant Gain (dB)	54	62.4	70.5
Pulse Length (us)	60	120	120
Bandwidth (MHz)	1.325	0.85	0.85
Resolution 3dB (m)	136	235	235
Zmin (dBZ)	**2.5**	**-21.1**	**-16.9**

CloudCube: Ka-band Channel

- CloudCube's Ka-band (35.75 GHz) subassemblies are build to print from RainCube's.
- RainCube Instrument occupied 4.5U of a 6U S/C. Repacking of the Ka-band H/W allows for a smaller envelop of 12.5 cm x 18 cm x 10 cm.
- Assembly and test of different subassemblies are underway.



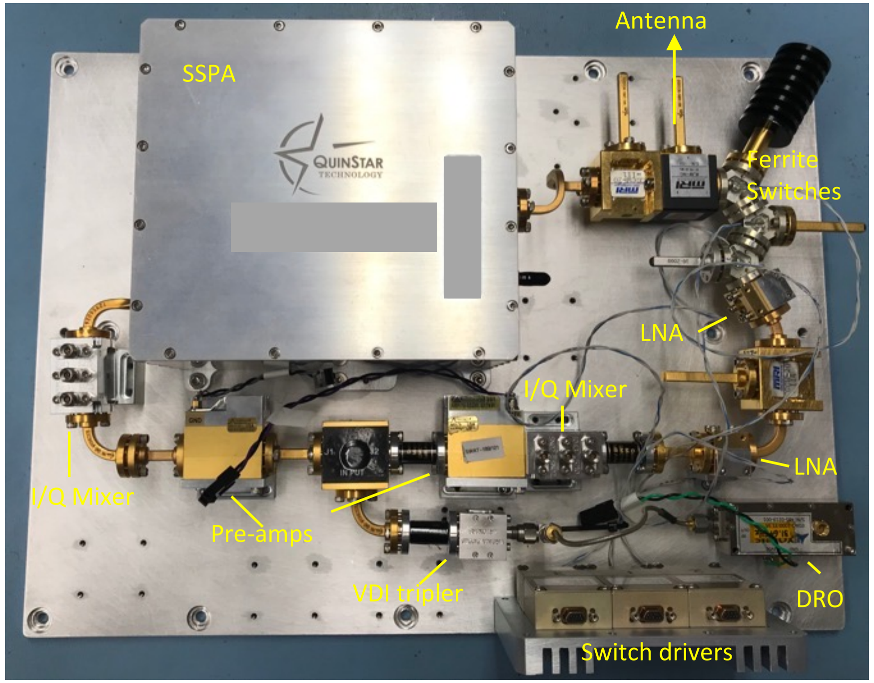
Fully assembled RainCube spare part
Components available from RainCube, but not fully assembled
Parts procured through the SRTD-18/19 and the IIP-19



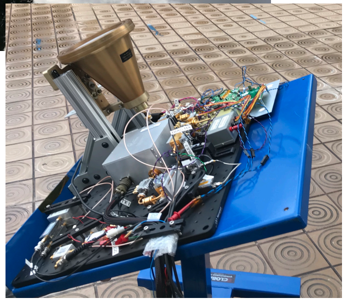
CloudCube's Ka-band EM Unit assembly

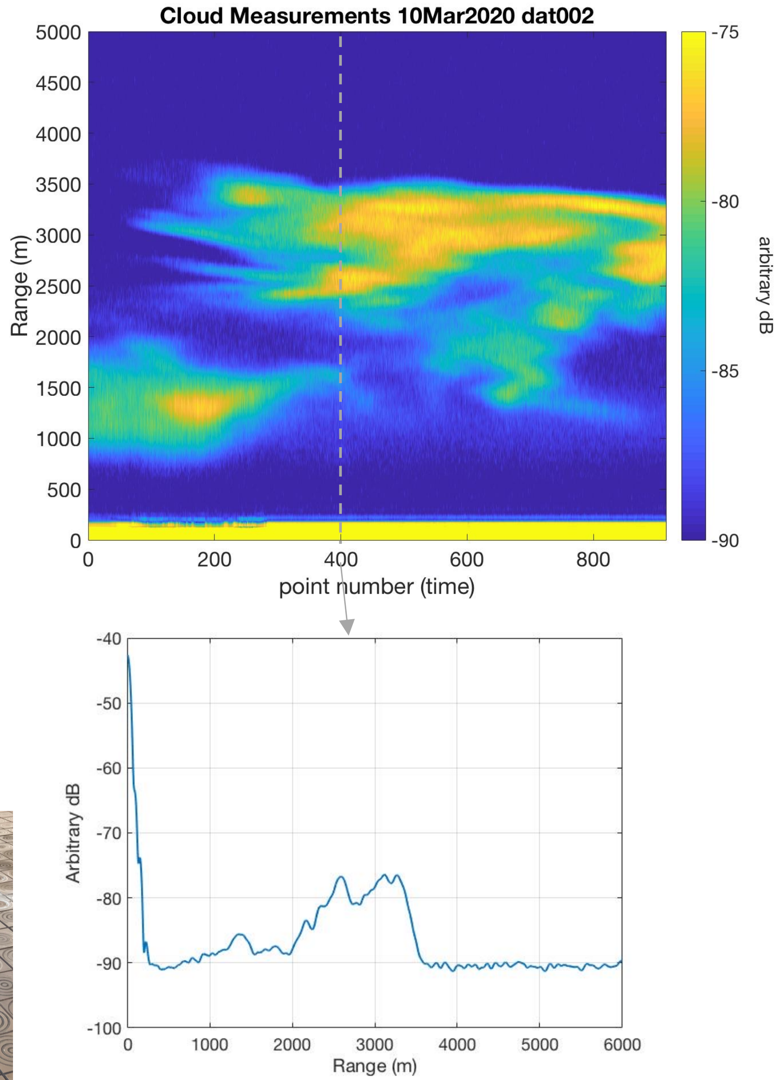
CloudCube: W-band Channel

- Compete W-band radar prototype with discrete radar components commercially available and JPL's designed.
- **The demonstration, for the first time, of the direct up/down-conversion radar architecture with pulse compression at W-band**.



CloudCube's W-band breadboard



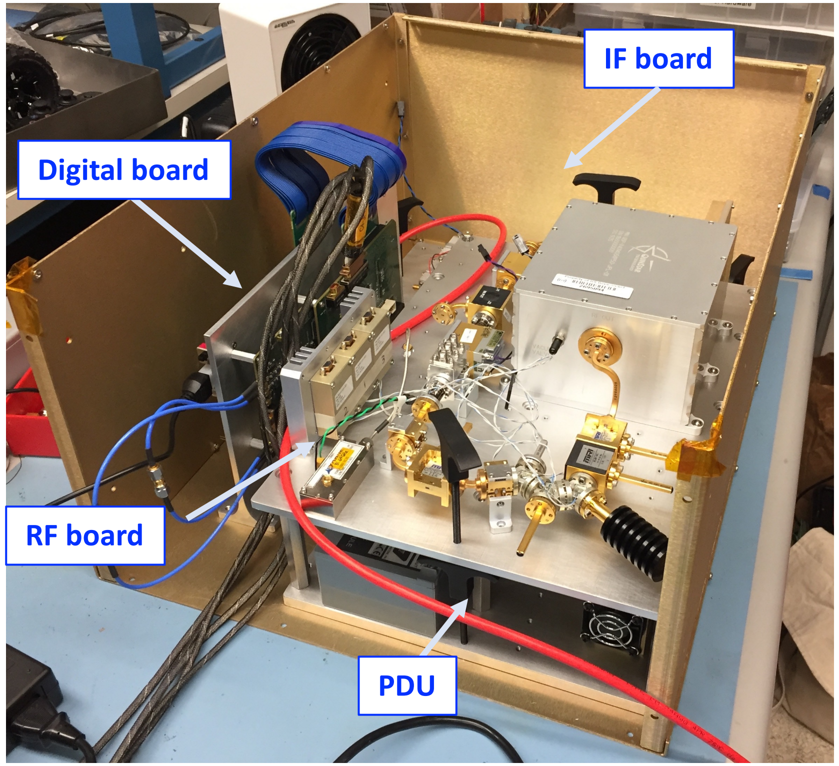


CloudCube's first cloud measurements

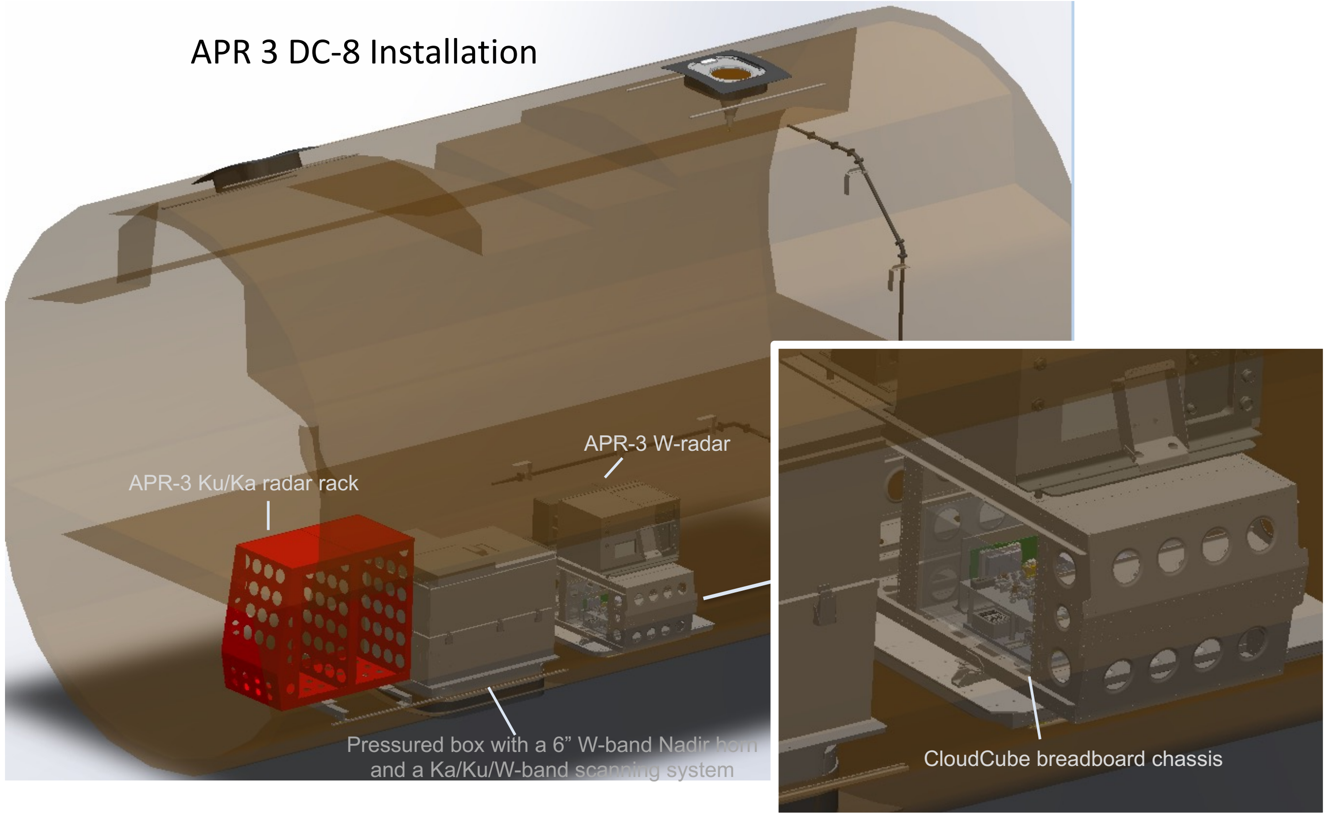
R. R. Monje et al. "A compact W-band breadboard radar for Atmospheric Measurements," 2020 IEEE Radar Conference (RadarConf20), 2020, pp. 1-4, doi: 10.1109/RadarConf2043947.2020.9266363.

CloudCube: W-band Airborne Demonstration

- As part of a JPL-SRTD initiative, CloudCube (W-band breadboard only) will join APR-3 as a tech-demo on the CPEX-AW (Convective Processes Experiment – Aerosols & Winds) field campaign in the Caribbean planned for August and September 2021

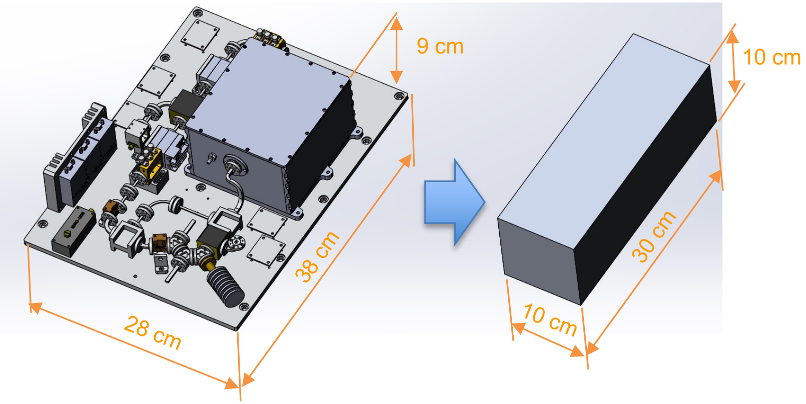


CloudCube airborne breadboard   19W x 22D x 10.5H (in)



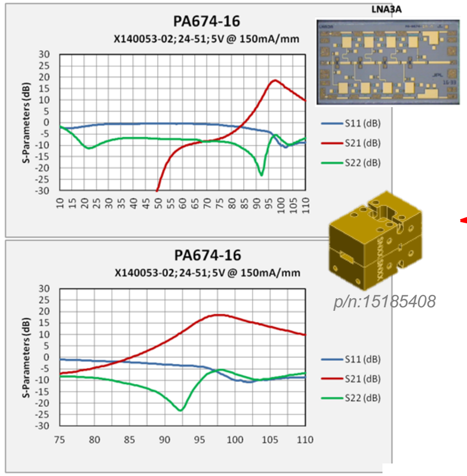
CloudCube: W-band Channel Cont.

- Reduce the RF electronics volume to fit within <3U

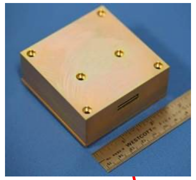


- Design 3 integrated blocks:
  - UCPA: up-conversion I/Q mixer, 2 pre-amps and attenuators.
  - LO Chain: 2 pre-amps, a power splitter and a tripler.
  - DCA: 2 LNAs, a coupler and down-conversion I/Q mixer

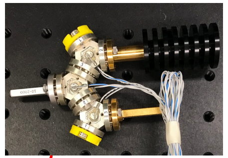
JPL GaN LNA, power dissipation 150 mW

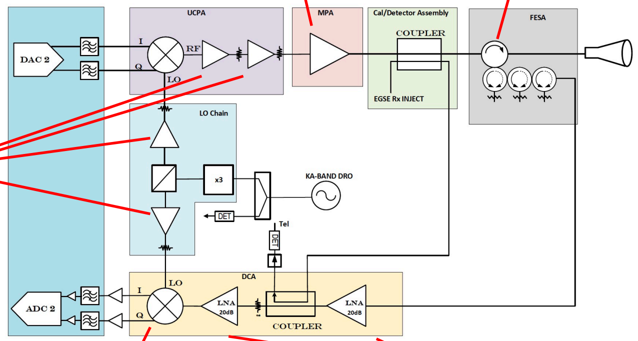


Raytheon 16 W puck



Honeywell/EMS Switches

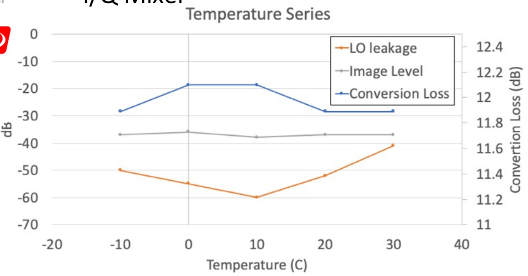


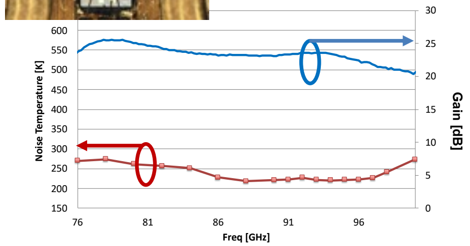


JPL's LNA

gotMIC
gMDR0013 B
W- and E-band IQ mod/demod
70 – 100 GHz

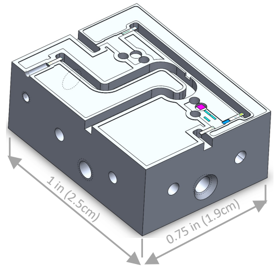
I/Q Mixer





JPL W-band LNAs Noise Temperature and Gain

Preliminary DCA integrated block with 2 LNAs, a coupler and a test port.



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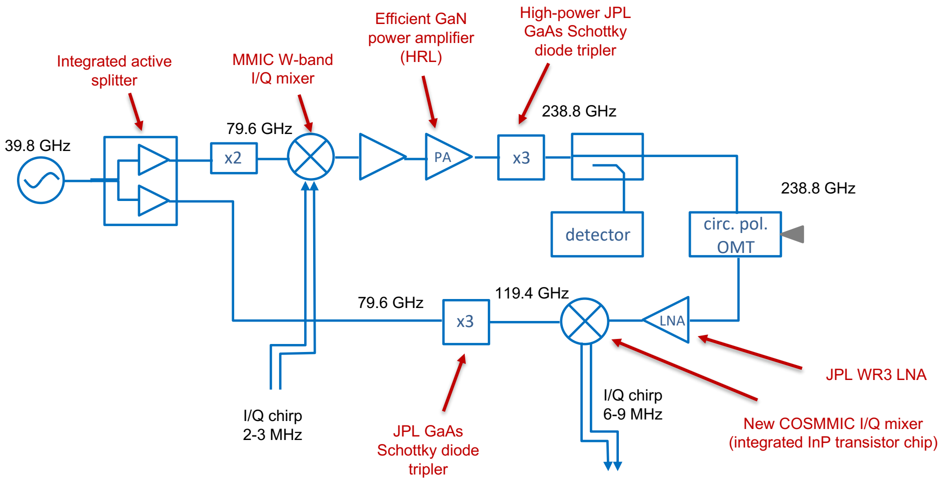
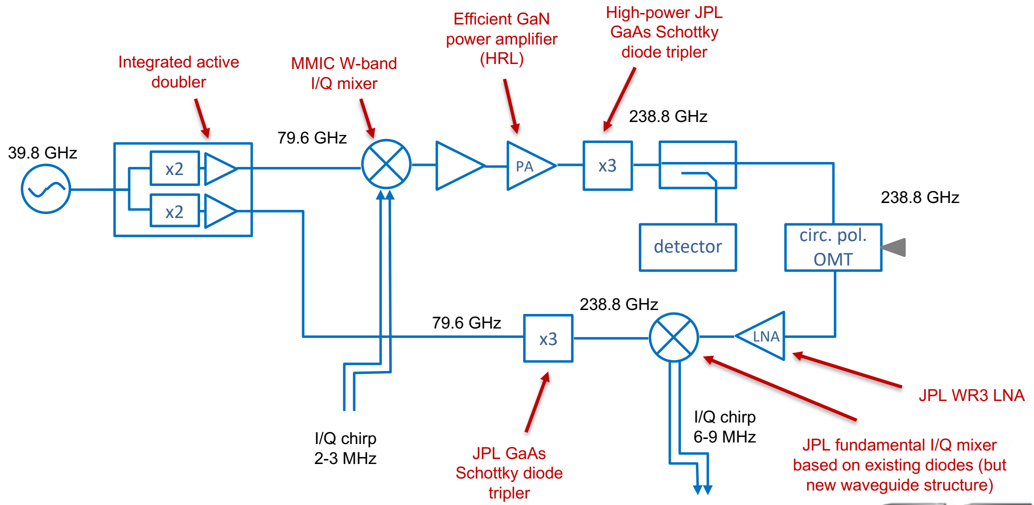
CloudCube: G-band Channel

- Goal of 0.5 W transmit power using power-combined Schottky diode triplers
- Utilize JPL's InP low-noise amplifiers
- Model RF architecture on lower channels, with direct up- and down-conversion using I/Q techniques
- Develop first use of I/Q 240 GHz mixer
- Separate transmit and receive using a waveguide orthomode transducer
- Build piecewise test-bench first for validation, then integrate components into compact waveguide block

<u>Version 1</u>: uses new JPL InP I/Q subharmonic mixer (active transistors) from COSMMIC effort

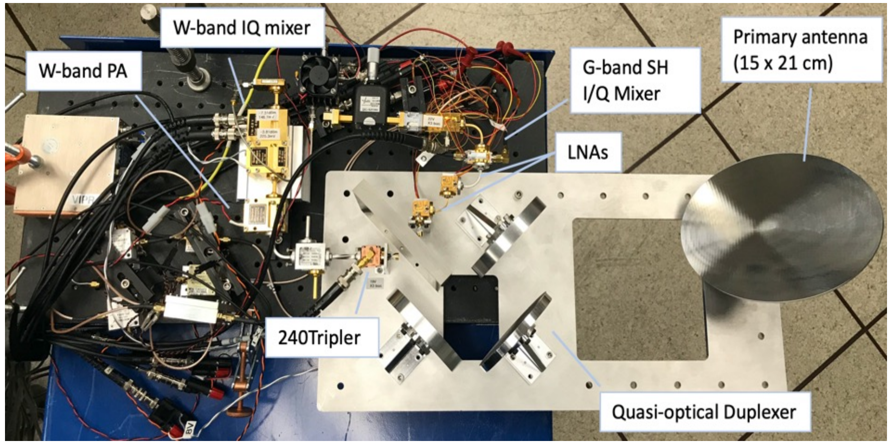


<u>Version 2</u>: uses fundamental GaAs Schottky diode JPL I/Q mixer



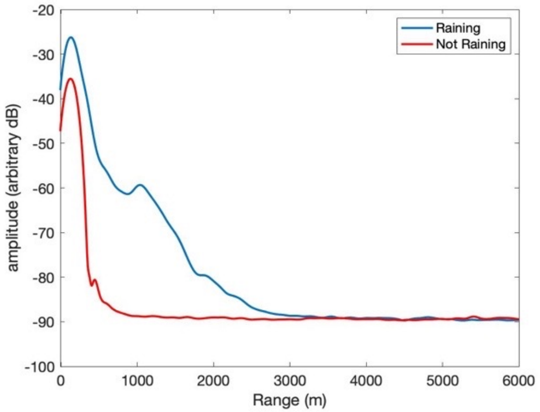
CloudCube: G-band Channel

- Built and test the first atmospheric G-band (239 GHz) breadboard radar



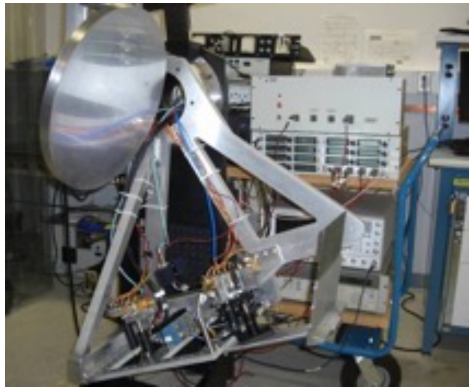
- Tx/Rx isolation of more than 80 dB using a quasi-optical duplexer system
- A transmit power of 30 mW using a single-chip 230 tripler.
- State-of-the-art 230 GHz LNAs with noise temperature 600K.

- On April 2021, we performed first ground-based measurements.

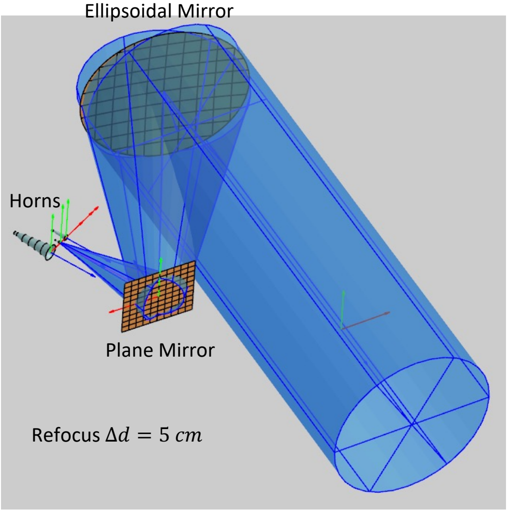


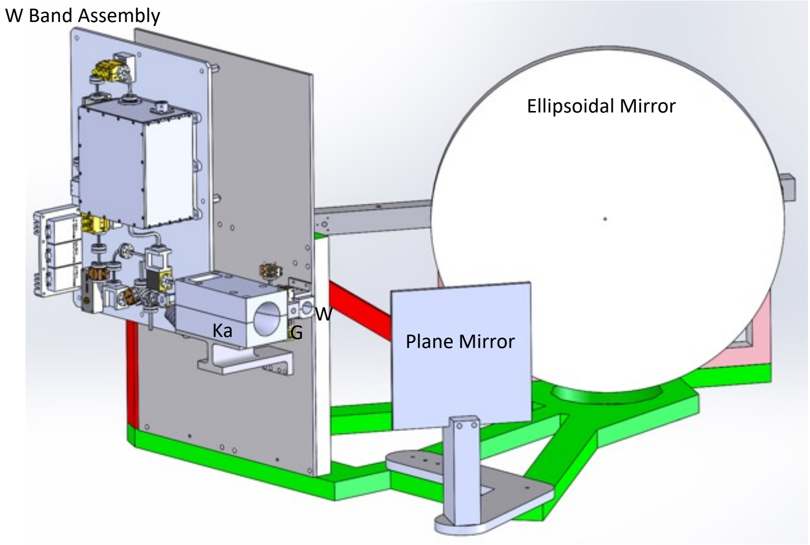
- Rain detection up to 2.5 km

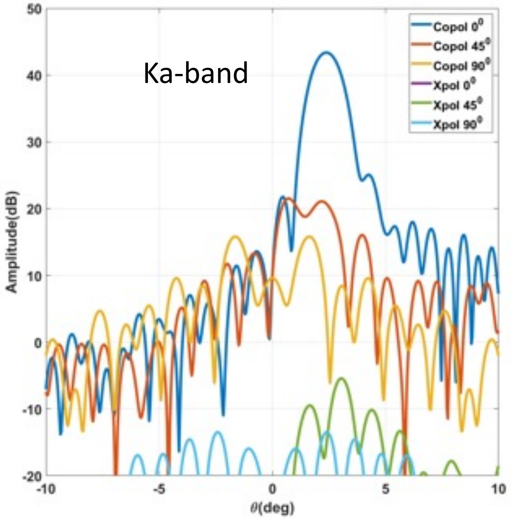
Lab and Ground Testing Optics

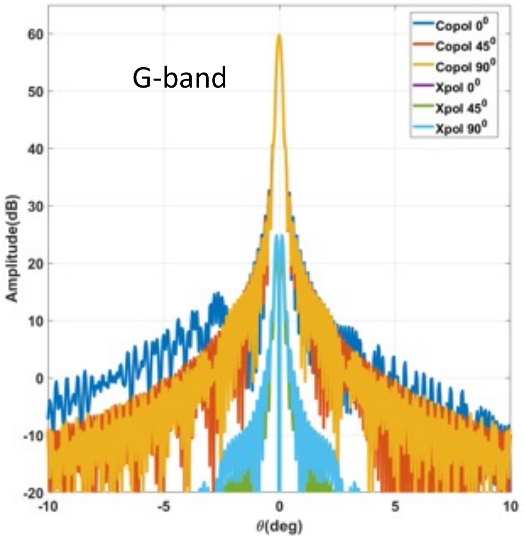


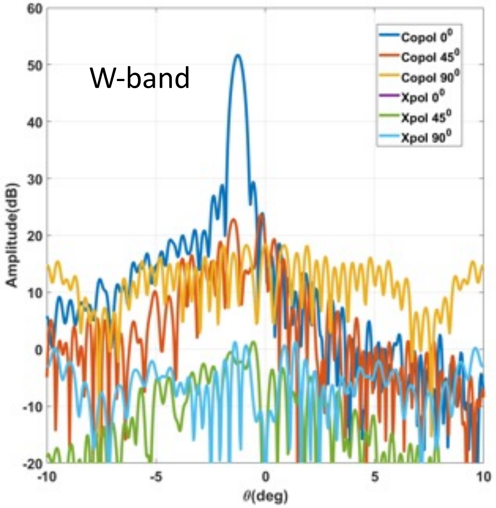
Repurposing an existing ellipsoidal mirror from a 600 GHz imaging radar





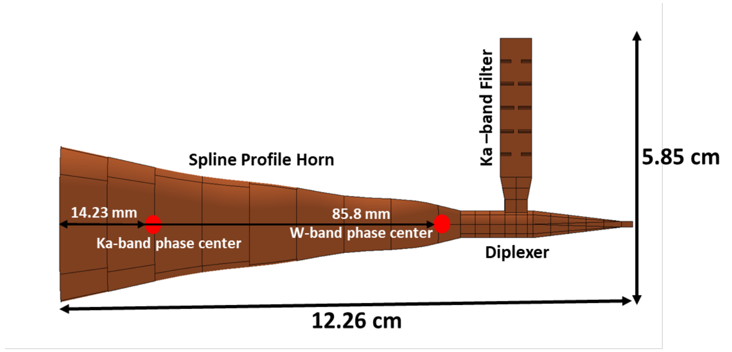


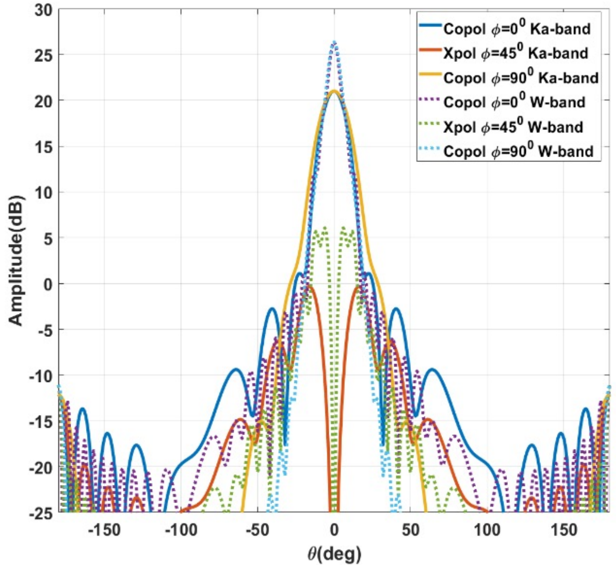




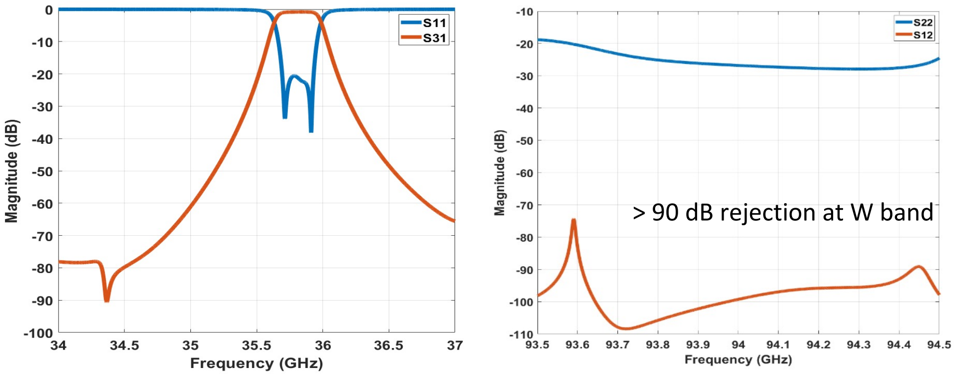
Multi-Frequency Horn Designs

W/Ka-band Horn



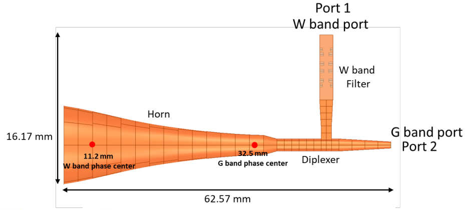


Ka-band filter

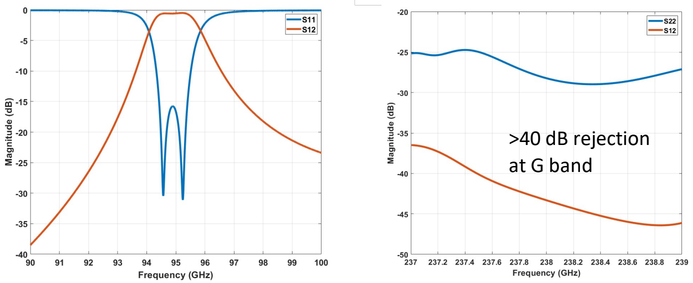


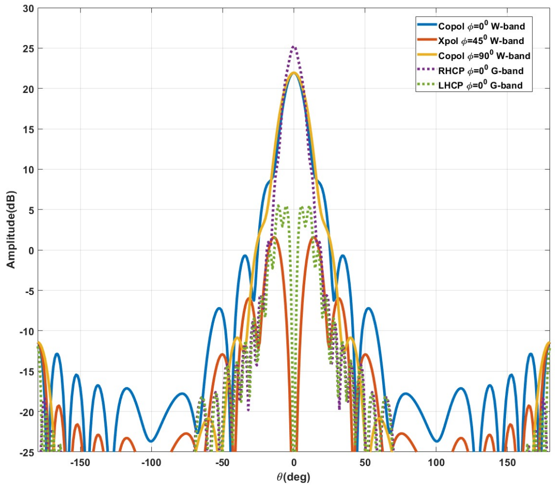
Nagaraja, S. P. M., Rodriguez Monje, R., Cofield, R., "*Dual frequency feed horn design for a compact cloud and precipitation radar operating at Ka- and W-band*" for presentation at ICEAA / IEEE APWC / USNC-URSI RSM, August 9-13, 2021, in Honolulu, Hawaii, USA.

W/G-band Horn



W-band filter

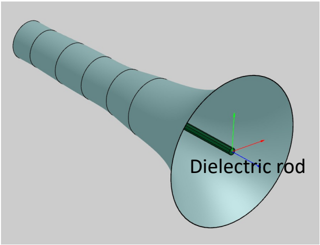




Ka/W/G-band Horn

<u>Options under study</u>

- Dielectric rod loaded horns
- Spline profile horns
- Ridge Horns



Potential Dielectric rod loaded horn representation

<u>Diameter d of the dielectric rod</u>

$$\frac{d}{\lambda} \leq \frac{0.7655}{\sqrt{\epsilon_r - 1}}$$

$d \leq 0.578\ mm$ for quartz strip ($\epsilon_r = 3.78, tan\delta = 0.0001$)
$at\ G - band\ (239\ GHz)$

CloudCube Next Steps

Short term:

- Fully characterize the different Ka- subsystems separately and a system as a whole.
- Test the RainCube's digital board design to add DPCA Doppler capabilities.
- Finalize the W-band integrated blocks design.
- Fabrication and test the different W-band integrated blocks for each subsystem, including the digital board and the module as a whole.
- Assemble and test the G-band transceiver from standard discrete blocks.
- Begin the design of integrated blocks of the different subsystems for the G-band channel.
- Fabrication and test of the multi-frequency horn.

Long term:

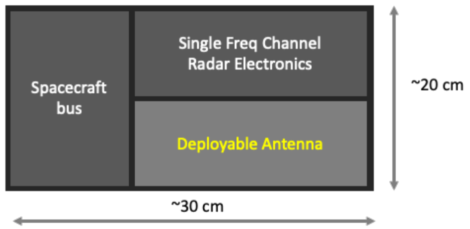
- Demonstrate multifrequency radar measurements.
- Complete environmental testing.

CloudCube Spacecraft Accommodation

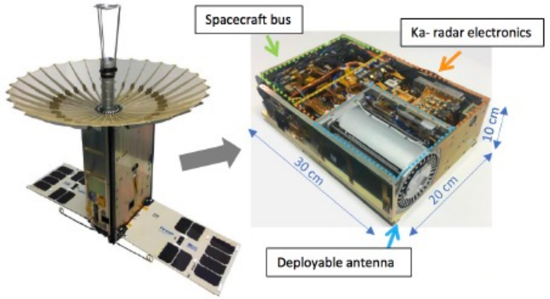
CloudCube falls into the compact and affordable radar instruments class that will facilitate the deployment of constellations of identical instruments flying in LEO.

▪ CubeSat:

Single frequency radar configuration, reducing the instrument complexity, size, power and mass. It will require an antenna stow volume of 2-3U for a 1.6 m diameter (smaller diameter for a prototype/proof of concept, NASA InVEST).



Notional CloudCube's footprint

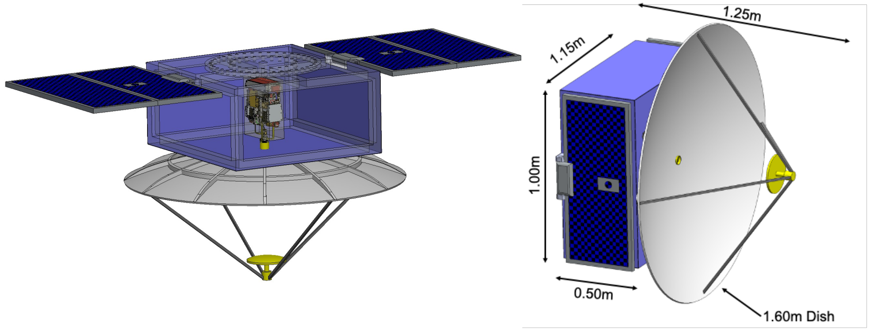


RainCube 6U

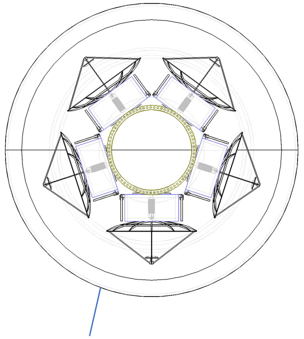
▪ SmallSat

With the current state of the art, CloudCube could be deployed only as part of a SmallSat payload with a standard solid reflector.

Reduce the cost of the mission by using hosted payload if we could reduce the mass and volume of the antenna (NASA InVEST, EVs).

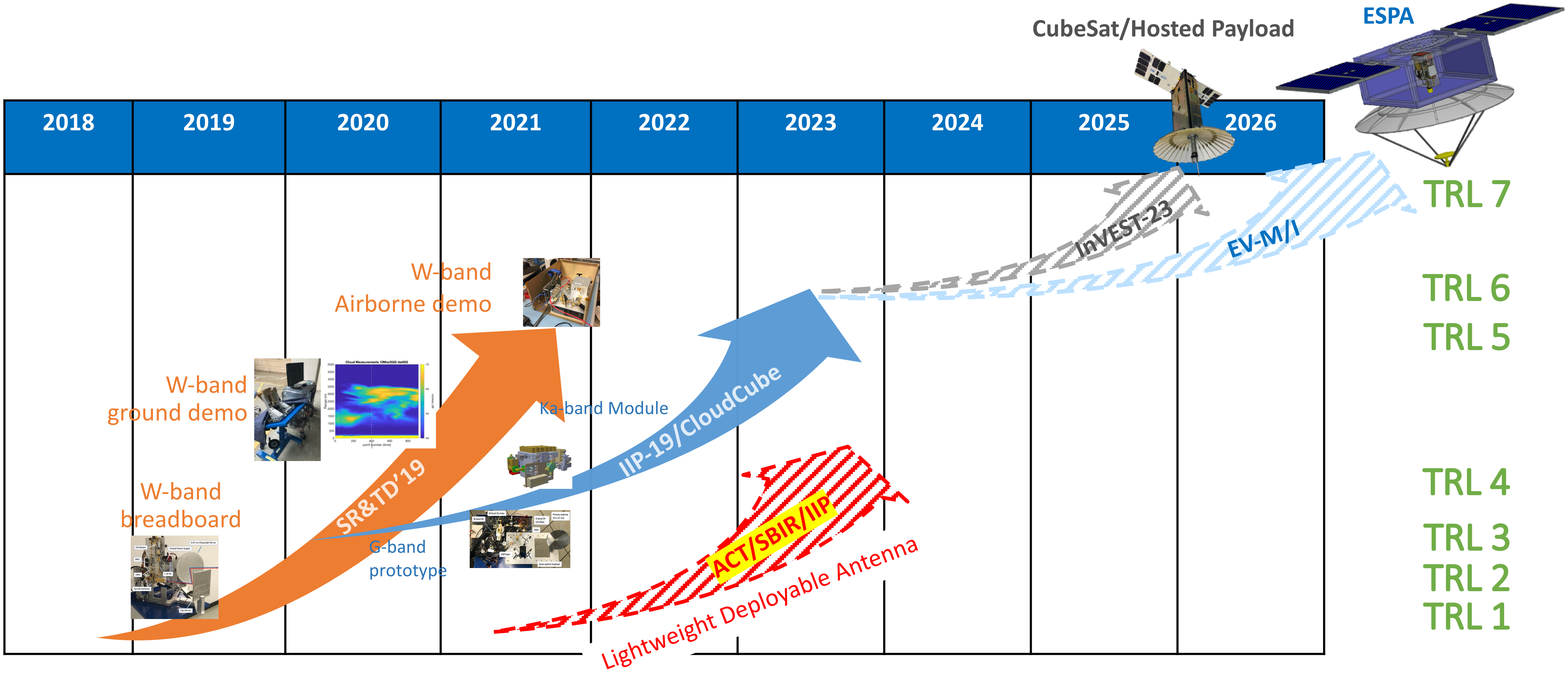


CloudCube in a notional ESPA Platform



Spacecraft configuration on an ESPA inside a Falcon 9 5.2 m fairing

CloudCube's Technology Roadmap



Future Mission Concept: ENTICE

Mission Objective: ENTICE (Earth's NexT Generation ICE) mission will provide direct global measurement of ice particle size along with associated atmospheric states, which would constitute in improving ice cloud microphysics parameterization, precipitation forecasting, more accurate quantification of cloud radiative effects, improved understanding of aerosol-cloud interactions and more accurate cloud ice and precipitation retrievals from remote sensing measurements.

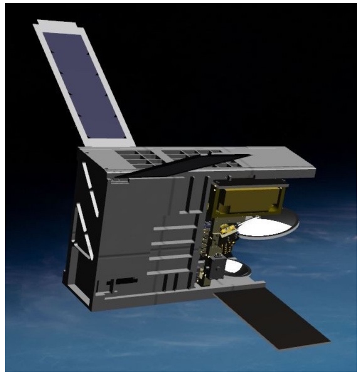
ENTICE Instrument Package

Passive radiometers suite

Channel	Center frequency	Offset frequency	Bandwidth
1	118.75	1.1	0.4
2	118.75	1.5	0.4
3	118.75	2.1	0.8
4	118.75	5.0	2.0
5	183.31	1.0	0.5
6	183.31	3.0	1.0
7	183.31	6.6	1.5
8	243.20	2.5	3.0
9	310.00	2.5	3.0
10	380.20	0.75	0.7
11	380.20	1.80	1.0
12	380.20	3.35	1.7
13	380.20	6.20	3.6
14	664.00	4.20	4.0
15	850.00	4.50	4.0

94 GHz Radar:

Reflectivity simulated at 0.5km resolution from surface to 16 km



- More frequencies can be simulated: e.g. GPM DPR

References: Jiang et al. 2019; 2017

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2019EA000580

https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2017EA000296

EV-M/EV-I: The combined ENTICE radar and radiometer will demonstrate the significant value of combining radar and radiometer observations for improving knowledge of cloud and convective processes necessary for quantifying high cloud feedback.

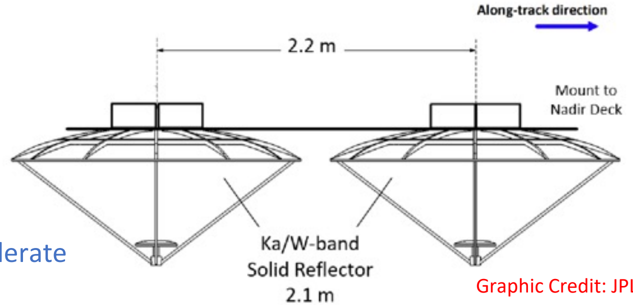
CloudCube and the ~~ACCP~~ AtmOS Mission Concept Study

- CloudCube/IIP development has been critical to increase the competitiveness of JPL for the initial ACCP mission concept study.
  - A CloudCube-like instrument is the leading radar candidate for ACCP mission currently starting pre-phase A.
  - As part of the mission concept study a number of needed breadboard and component-level tests have been carried out to demonstrate the suitability of the JPL's W- and Ka-band radar for all of the potential preferred ACCP concepts.
- The current AtmOS radar instrument, DORA (DOppler RAdar), has evolved into a more complex instrument than CloudCube
  - ACCP will use some technology infusion from CloudCube's development (Pre-Phase A starting in Spring of 2021).

Two AtmOS Radar Concept

DORA-C

Ka and W-band
Polar orbit



Graphic Credit: JPL

Clouds, Precipitation, Light-to-Moderate Convection, and Snowfall

Vert. Res./Window: 100 - 170 m / 25 km
Detection Sens.: 0 dBZ (Ka), -25 dBZ (W)
Doppler Accuracy: 0.3 to 0.5 m/s

Medium-Sat Compatible

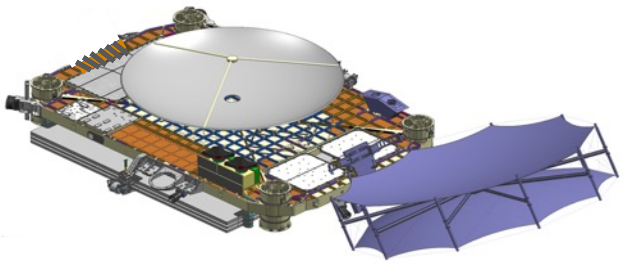
Size: 430 cm x 210 cm x 85 cm
Weight: 157 kg
Power: 360 W

TRL: 4

Heritage: AirSWOT, Airborne Precip. Radar (APR), RainCube, CloudCube

DORA-D

Ku and W-band
Inclined orbit



Graphic Credit: SPACEX, JPL

Clouds, Precipitation, and Convective Storms

Vert. Res./Window: 100 - 210 m / 25 km
Detection Sens.: +10dBZ (Ku), -25 dBZ (W)
Doppler Accuracy: 0.7 to 1.0 m/s

Small-Sat Compatible

Size : 280 cm x 210 cm x 172 cm (stowed)
Weight: 135 kg
Power: 332 W

TRL: 4

Heritage: Same as Dora C

Thank you!